R&D on Industrial Heat Pumps

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R&D ON INDUSTRIAL HEAT PUMPS

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Abstract: More than 80% of the total energy use in industry consists of the need of heat in the form of steam at different pressure levels and for firing furnaces. The total industrial heat use together with exothermic heat from chemical reactions is eventually released to the ambient atmosphere through cooling water, cooling towers, flue gasses, and other heat losses. This heat loss is called 'Industrial waste heat'. A first, most logical, solution to this waste heat problem is to reuse the heat within the same process through process integration or at the same site. If this is not possible, problems with temperature level, timing or location can be solved by heat pumping, heat storage or heat distribution. This paper focuses on heat pumping. European R&D and the goals set are defined by the European Technology Platform on Renewable Heating and Cooling (RHC-Platform) in their recent Strategic Research and Innovation Agenda for Renewable Heating and Cooling. Industrial heat pumps are an important part in that strategy. The report is presented to the European Commission as advice on which technology to support.

In the Netherlands an extensive program under ISPT focuses on heat pumping technologies tackling many of the topics raised under RCH. A general description of research and development projects is given where it should be noted that for confidentiality reasons, exact details of the process and the control and design alternatives for these projects are not provided and only described in general terms.

Key Words: heat pumping technologies, industry, working fluids, high temperatures

1 INTRODUCTION

The RHC-Platform has produced the present Strategic Research and Innovation Agenda for Renewable Heating and Cooling [1].

Heat pumps could save energy in industrial processes by recovering waste heat and lift the temperature to a level high enough for re-use.. Recoverable waste heat and process heat at moderate temperatures are found in food processing, paper and pulp, refineries, and chemical industry. Industrial heat pumps should be able to produce heat in the temperature interval between 100°C and 250°C and the temperature difference between heat source and heat sink of the heat pump should preferably be up to 100°C.

Efficiently providing heat for industry at temperatures higher than 80-100°C with heat pumps is difficult. Industrial heat pumps (for heating purposes) currently consist of closed cycle vapour compression, open cycle mechanical vapour recompression and Lithium Bromide (LiBr) heat transformers. These technologies are referred to as 'current heat pump technologies' in Figure 1. A broader range of operating temperatures and higher temperature lifts are needed to increase the application potential and the energy saving potential that heat pumps offer. The end users' demands extend beyond the required temperature and cost of the system to topics such as the toxicity & flammability of the working medium and the reliability of the system. No single heat pump technology can cover this entire range of demands, meaning different heat pump technologies should be developed in parallel. The main objective is the exploration of alternative thermodynamic cycles for heat-pumping and heat transforming for different industrial applications, with the goal to increase the operating window of industrial heat pumps so that they can deliver heat at medium pressure steam levels (app. 200°C).Not only will these improvements allow larger energy savings, but they will also unlock the benefits of economies of scale for the European heat pump industry.

Referring to the graph shown, the following developments can be foreseen, depending on the temperature levels of the application:

- Development of new working media and compressors (VC new working media) would allow to extend the operating range of conventional compression heat pumps above today's 100°C. New vapour compression systems should use low GWP synthetic refrigerants or natural refrigerants (such as butane or water) to reach temperatures of up to 150°C. Components and materials should be developed to achieve temperature lifts of up to 70 K.
- Development of new heat transformer concepts that allow upgrading of waste heat to temperatures as high as 200ºC without the use of external drive energy. These concepts can be applied when waste heat temperatures are sufficiently high (> 90°C).
- Development of hybrid systems that use both work and waste heat as driving force to extend the operating range compared to work or thermally driven systems. This allows for use of low temperature waste heat and still generating temperature lifts of up to 100 K.
- Finally, new concepts can be envisioned that use either work or high grade heat to drive the system and use new thermodynamic cycles that are able to operate at higher temperatures and generate higher temperature lifts in an economic way.

Developments for each of these four technology concepts will be described in this paper.

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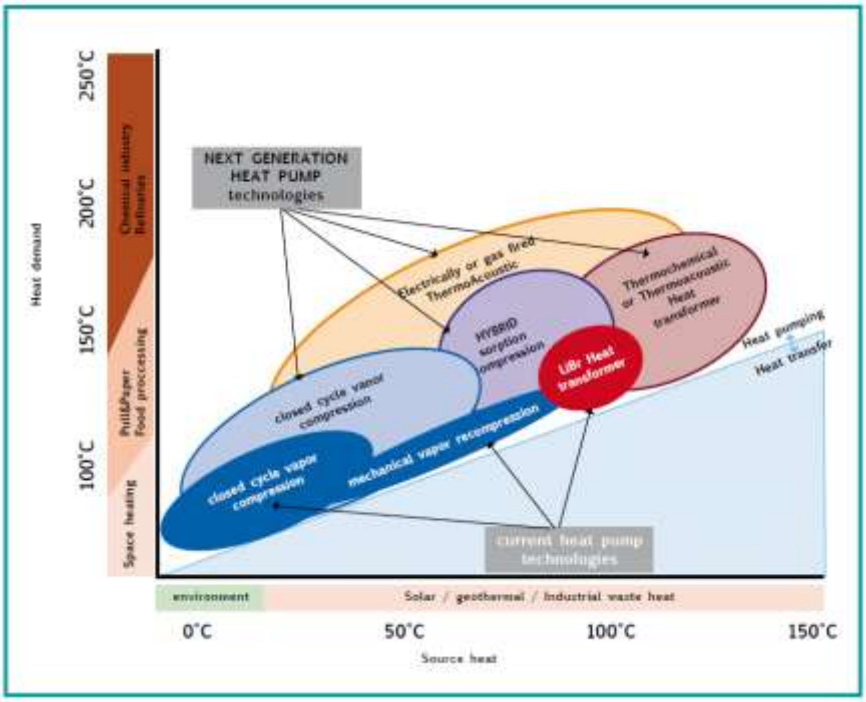

Fig 1 Heat pump technologies and their operating temperatures

Figure 1 plots the driving temperature ("source heat") against the delivered temperature ("heat demand") for various heat pump technologies.

Apart from their operating temperatures, these technologies have different levels of maturity. They form a chain of new heat pump technologies in which the mechanical vapour compression systems with new working fluids are the next generation to be tested at a small scale in real applications for higher delivery temperatures. The salt-ammonia sorption and thermo acoustic heat transformers are in the development stage of laboratory prototypes, proofing the concept of the system. The hybrid sorption-compression systems and gas fired thermo acoustic heat pumps are in the stage of proofing the principle.

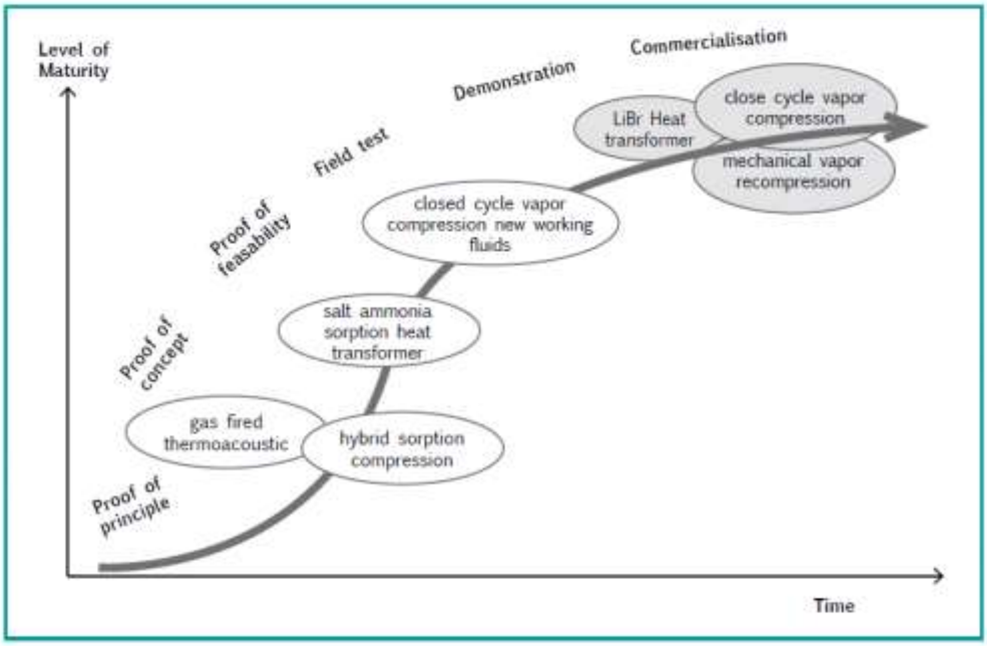

Fig 2 Development stages of new concepts for industrial heat pumps [1]

In their advice to the Commission the RHC Platform [2] has proposed:

	Research and Innovation Priorities	Predominant type of activity	Impact
CCT.12	Enhanced industrial compression heat pumps	Development	By 2020
CCT.13	Process integration, optimisation and control of industrial heat pumps	Demonstration	By 2020
CCT.14	Improvements in Underground Thermal Energy Storage (UTES)	Demonstration	By 2020
CCT.15	Improvement of sorption cooling from renewable energy sources	Development	By 2025
CCT.16	New concepts for industrial heat pumps	Research	By 2030

2 CLOSED CYCLE VAPOR COMPRESSION

Before 2005, heat pumps were merely refrigeration plants where pressures are increased to deliver condensing heat at temperatures of 35°C up to 50°C. This operation range also depends on the evaporation temperature, efficiency and pressure ratio. The refrigeration compressors have a design pressure of 25 bars. This is also a limit for higher condensing temperatures. The large manufacturers of industrial refrigeration in the Netherlands, i.e. GEA-Grenco with their seat in Den Bosch and IBK from Houten, have discovered this new market of high temperature applications and already executed projects A large application potential of industrial heat pumps is still not used because of these limited supply temperatures of about 100°C of commercially available heat pumps. If these supply temperatures could be increased, more industrial processes could be improved in their energy efficiency. The main reason for the limited temperatures has been the absence of adequate working fluids [3].

2.1 CO_2 – Heat Pump

Beginning of 2000 the refrigeration industry is introducing CO_2 again as refrigerant and secondary refrigerant. CO_2 is a natural refrigerant without ozone depletion potential and with a low global warming potential. It is therefore a sustainable alternative for the synthetic refrigerants such as the HFC types.
Since CO_2 is a high pressure refrigerant, the refrigeration industry had to develop equipment with design pressures up to 45 bars. It is this development that has led to the construction of 50 bar industrial compressors. Using these compressors with ammonia or HFC like R134a as refrigerant, high temperature heat pumps (HT heat pumps) can be produced for industrial purposes. Condensation heat at temperatures up to 80°C can be delivered in a large variation of capacities with good efficiency.

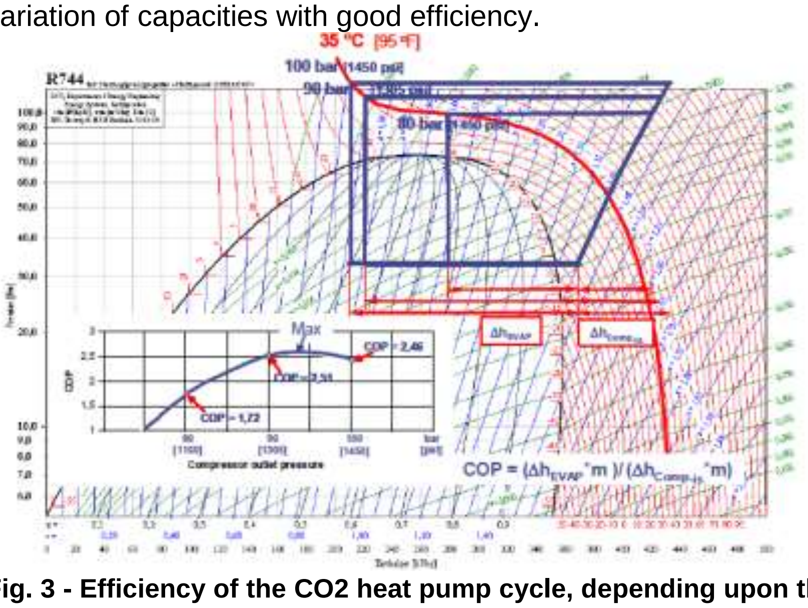

Fig. 3 - Efficiency of the CO2 heat pump cycle, depending upon the discharge pressure [source HPC]

HT heat pumps are also executed with CO_2 as refrigerant in a trans critical cycle. Larger units for water heating from 10° up to 70°C are available in a range up to 120 kW running with any heat source and can even produce cooled water (8°C). Essential is that the CO_2 at condensing pressure can be strongly cooled in order to maintain a sufficient efficiency. This is possible by a process flow that starts to heat up at e.g. 15°C. The subcooling of the CO_2 before expansion allows for a larger heat input and output for the same power of the compressor, therewith increasing efficiency. The COP of CO_2 can be higher than ammonia in case of high temperatures differences. Compressor sizes for these high pressures are however limited available.

2.2 n-Butane heat pump

With the search into natural refrigerants for heat pumps the refrigerant, n-butane is regarded as a proper medium in high temperature heat pumps with condensing temperatures up to 120°C. These temperatures can be reached in standard 25 bar compressors. This type of HT heat pump is based on conventional, reliable refrigeration design with special safety attention and features for safety. Several feasibility studies have been carried out in industry and refrigeration contractors nowadays offer the HT heat pumps.

The feasibility studies show the technical and economic implications that arise when integrating the n-butane heat pump in existing installation. To integrate a heat pump it is necessary to redesign the original process and thus the equipment (heat exchangers, process layout). This should clearly be a task for manufacturers and suppliers of process equipment.

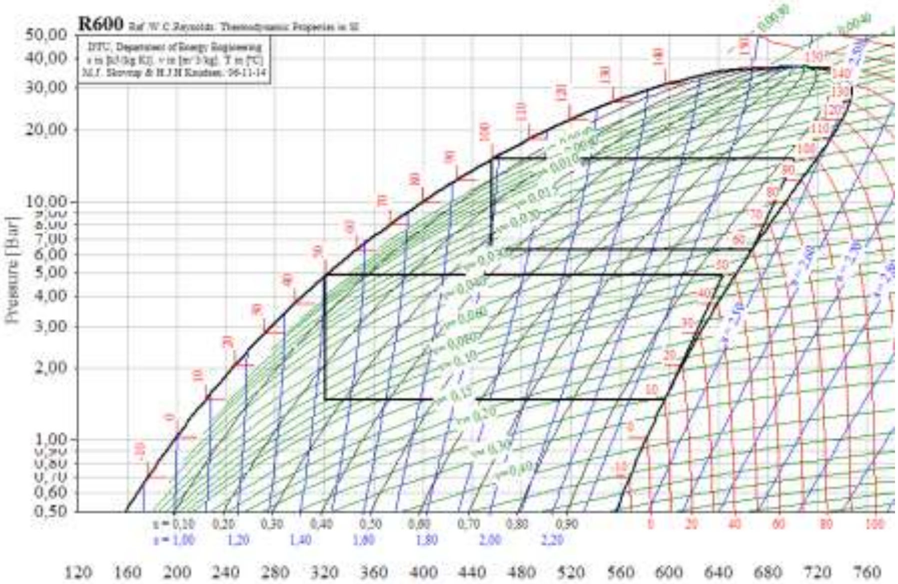

Fig 4 - n-Butane heat pump cycle (at 60/100°C: COP=7.1 and at10/50°C: COP=6.8) (source GEA-Grenco)

As can be seen in Figure 4, the n-butane gas is compressed in the gas-liquid area of the n-butane Mollier (log p-h) diagram. Therefore it is necessary to preheat the suction gasses before they enter the compressor to avoid problems (damage valves, disrupt lubrication) with liquid in the compressor. This can be executed in heat exchangers that simultaneously heats up the suction gas and cools down the liquid after condensation. This is a regular design aspect in refrigeration installations.

2.3 New refrigerants

An interesting paper is presented at the 11th Heat Pump Conference in Montreal 2014 [4], where it is stated that an ideal working fluid should be non-flammable, non-toxic and should have a low GWP, no ODP and a high critical temperature. Four ideal working fluids are identified: LG6, MF2, R1233zd and R1336mzz.

Working fluid	T_{crit} [°C]	Flammable or toxic	ODP	GWP
R1233zd	166	no	0.0003	6
R1336mzz	171	no	0	9
LG6	>165	no	0	1
MF2	>145	no	0	<10

Table 1: Properties of ideal working fluids for high temperature use [4]

Important producers of these new working fluids with high condensation temperatures and low GWP are Honeywell, Siemens en DuPont. First pilots are reported of.
Interesting is the development of LG6 by Siemens [5] showing a temperature lift of 50 K with an experimental COP of 4.8.

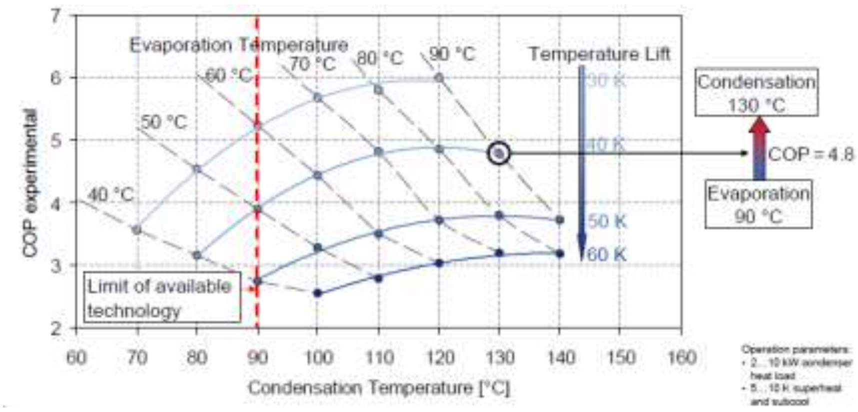

Fig. 5 LG6 Siemens

3 THERMOCHEMICAL AND THERMOACOUSTIC HEAT TRANSFORMER

Heat transformers can be applied in cases where waste heat is available at sufficient high temperatures (> 90-100ºC). The advantage of these concepts is that they don't require additional energy to drive the system. Typical efficiencies are 25-30%, meaning that this fraction of the waste heat can be reused in the process. Disadvantage of a heat transformer is that the other part of the waste heat still needs to be cooled to the ambient atmosphere. The general concept of a heat transformer is depicted in Figure 6 below.

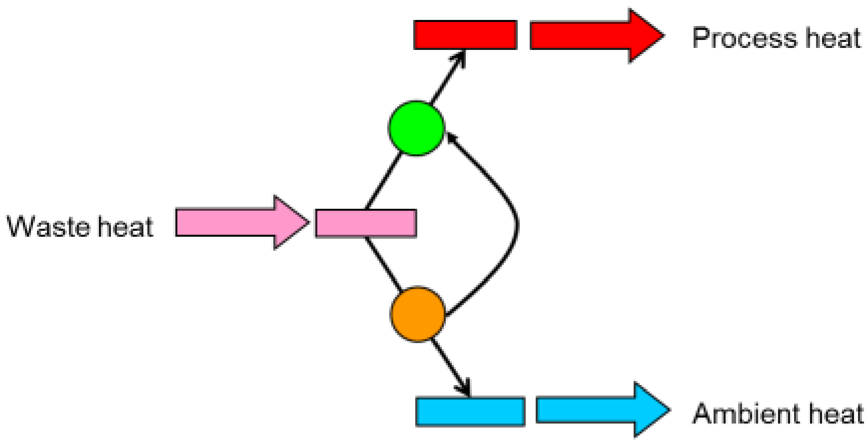

Figure 6 Thermodynamic concept of a heat transformer

Two technological principles are being applied at ECN to realise this heat transformer. These principles are based on thermoacoustics and thermochemistry.

3.2 Thermo Acoustic Heat Transformer

Thermoacoustic (TA) energy conversion can be used to convert heat to acoustic power (engine) and to use acoustic power to pump heat to higher temperature levels (heat pump). The systems use an environmentally friendly working medium (noble gas) in a Stirling-like cycle, and contain no moving parts. Although the dynamics and working principles of TA systems are quite complex and involve many disciplines such as acoustics, thermodynamics, fluid dynamics, heat transfer, structural mechanics, and electrical machines, the practical implementation is relatively simple. This offers great advantages with respect to the economic feasibility of this technology.

When thermal energy is converted into acoustic energy, this is referred to as a thermoacoustic (TA)-engine. In a TA-heat pump, the thermodynamic cycle is run in the reverse way and heat is pumped from a low-temperature level to a high-temperature level by the acoustic power. This principle can be used to create a heat transformer, as depicted in Figure 7.

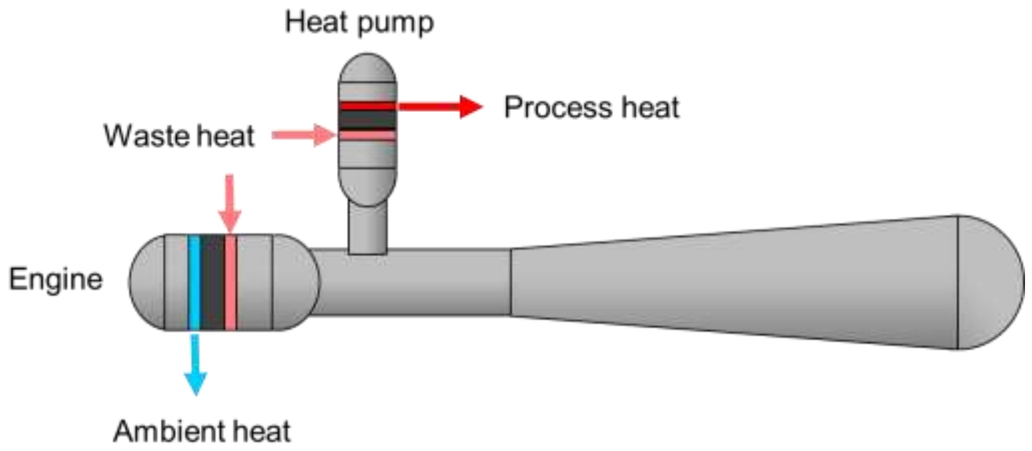

Fig. 7 TA heat transformer

The TA-engine is located at the left side and generates acoustic power from a stream of waste heat stream at a temperature of 140ºC. The acoustic power flows through the resonator to the TA-heat pump, located on top of the resonator. Waste heat of 140ºC is upgraded to 180ºC in this component. The total system can be generally applied into the existing utility system at an industrial site. The picture below gives an experimental setup of a 10 kW system

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Fig. 8 Thermo acoustic heat transformer at ECN

3.3 Thermochemical heat transformer

Thermochemical heat pumps use the heat released/dissipated during ad/desorption of gas in solids to create a heat pump cycle. This process consists of an alternating cycle consisting of a discharge phase and a regeneration phase, in which the solids are generating heat during adsorption of the gas, respectively require heat to release the adsorbed gas from the solid.

The system operates at three temperature levels. These temperature levels are the waste heat temperature, the ambient temperature and the temperature of the upgraded heat. The system consists of two reactors, each containing a different salt. For this specific system use is made of lithium chloride as low temperature salt (LTS) and magnesium chloride as the high temperature salt (HTS). Ammonia vapour is exchanged between these two salts. Industrial waste heat is used to free the ammonia from the LTS. The ammonia flows, driven by the pressure difference between the two reactors, to the HTS and reacts with the HTS. This exothermic reaction delivers heat at high temperature. During the regeneration step the ambient temperature cools the LTS and the waste heat heats the HTS. The ammonia vapour flows back to the LTS under these conditions. The scheme below shows the implementation of such a system in an industrial process. Both the LTS and HTS reactor vessel are built in twofold in order to achieve a continuous system. A switching control system determines whether the above pair of reactor vessel are loading (regenerating) or discharging. The other vessels are running in the reverse process.

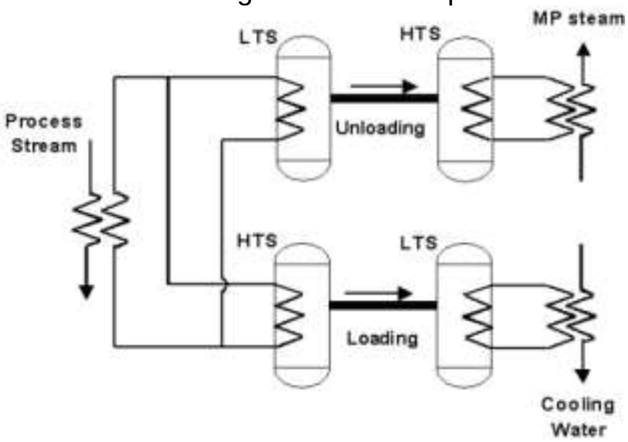

Fig. 9 Thermochemical heat pump transformer

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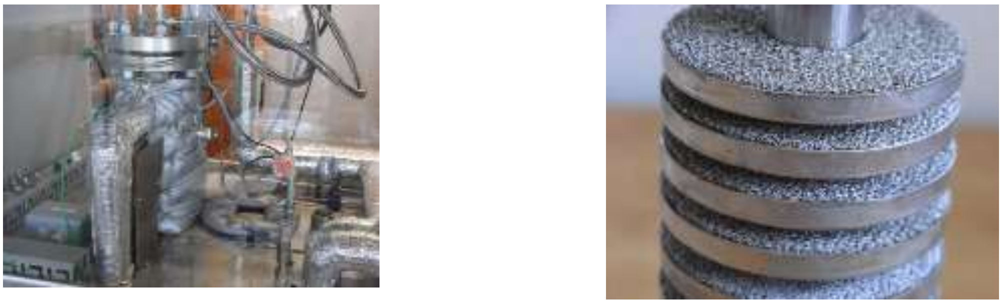

Fig. 10 Thermochemical heat pump component testing

Figure 10 shows picture of a reactor element that is used to measure the heat uptake and release by the salt during cycling experiments. Lab-scale experiments have shown that the required operating temperature and temperature lift can be achieved. Business cases have been evaluated with industrial end-users from the chemical & refining industry which show positive economic results. Important requirement is the power density which is the main challenge.

4. HYBRID SYSTEMS

4.1 Thermochemical heat transformer

This system is an extension of a regular thermochemical heat pump. The extension consists of a compressor that adds flexibility to the system with respect to operating temperatures, and more important, enables to use of lower temperature waste heat than the system without compressor.

The final requirements for this application are:

- Driven by a compressor and waste heat in the temperature range 50 - 150°C;
- Delivering process heat in the temperature range up to 250°C, with process heat temperature at least 50°C higher than the waste heat temperature;
- System efficiency (process heat out/waste heat in) >25%, depending on operating temperatures, (average) Electrical COP > 5;

Figure 11 depicts the thermodynamic concept (right side) of this hybrid concept and a picture of the setup (left) that has been used to test a compressor under batch type operating conditions.

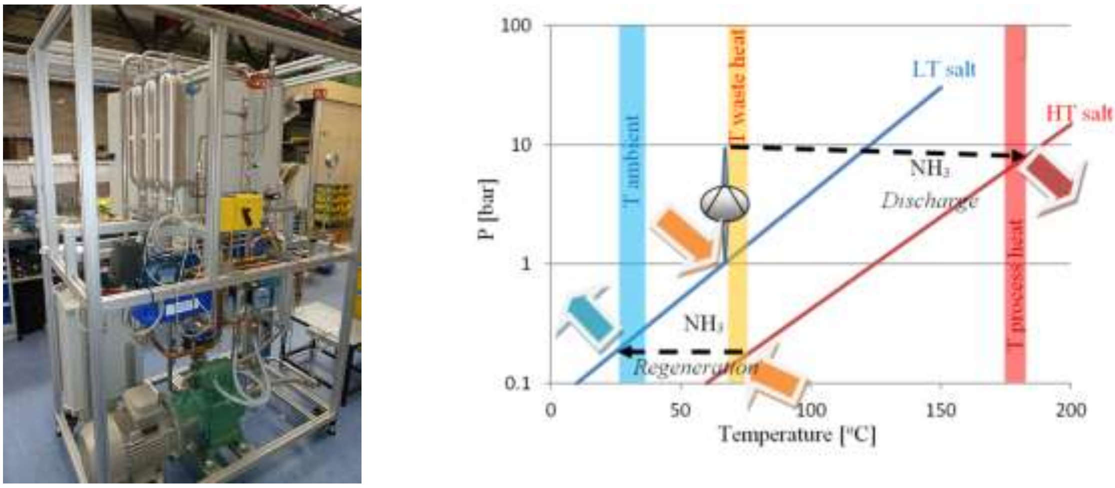

Fig. 11 Hybrid Thermochemical-compression heat pump testing

4.2 Compression Resorption Heat Pump

Usually, heat pumps work best if the heat added or extracted at a constant temperature. However, several applications exist where the temperature of the streams will change as heat is added or extracted. The temperature difference over the glide leads to an extra exergy loss over the heat exchanger, unless the working fluid of the heat pump has the same glide. This principle is applied in the Compression Resorption (CR) heat pump. In the CR heat pump the working fluid is a zeotropic mixture, usually ammonia-water. The composition of this mixture is adjusted until the glide of the working fluid optimally matches the glide at the process stream.

The cycle can be designed to show a temperature glide in the resorber that corresponds to the temperature glide of the industrial waste flow that has to be heated. For specific operating conditions the cycle performance is significantly better than for the vapour compression cycle. The main problem of the cycle is the compressor that has to be suitable for oil-free wet compression and still show acceptable isentropic efficiencies. Hybrid Energy solves this problem by separating the liquid and vapour and compress these separately. A higher efficiency could be obtained if a compressor would be available that could compress the mixture. These compressors must be suitable for high compression ratios and for simultaneously compress vapour and increase the liquid pressure. The compressor should further be not sensible to liquid carry over.

The main goal of the developments at the Technical University of Delft is a wet compressor that is suitable for operation in compression resorption heat pumps.

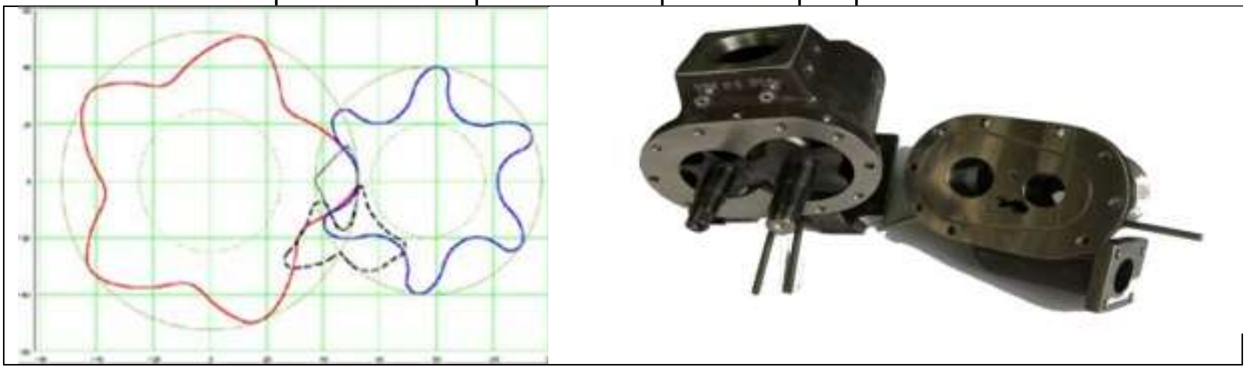

Fig. 12 Principle of compression and prototype of compressor

In addition, large efforts have been put into the development of new multichannel re/absorbers that would be much more compact compared to conventional heat exchangers.

5. ELECTRICALLY AND GAS-FIRED THERMOACOUSTIC SYSTEMS

The working principle of TA heat pumps has been described above. Since TA systems use a noble gas as working medium, these systems can be applied in a wide range of temperatures unlike regular compression or sorption heat pumps. Using this property of TA systems, ECN is developing two types of heat pumps, with two different drivers: mechanically and gas-fired.

A 10 kW mechanically driven system has been developed by ECN and Bronswerk Heat Transfer and is shown in Figure 13. This system is presently tested and subject of another paper at this conference.

Fig. 13 Electrically driven thermoacoustic system

A thermoacoustic system can also be driven by high temperature heat, for example generated by a gas burner. Biggest challenge here is to transfer the heat from a gas burner to the thermoacoustic system. Figure 14 below shows the thermodynamic represention of this system (left) and a picture of an experimental thermoacoustic engine that is heated by hot flue gasses.

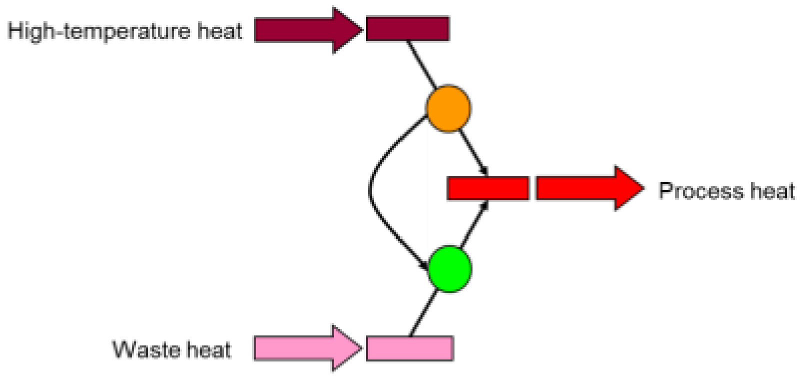

Fig. 14 Thermodynamic scheme for gas-fired TA heat pump (left) and photo of the engine part

Both systems have virtually no limits with respect to operating temperature, other than the structural integrity limits of the pressurized resonator. In addition, large temperature lifts can be generated which means that these general concepts can be applied in a large variety of applications.

6. CONCLUSIONS

The operating window of industrial heat pumps can be roughly defined from economic and thermodynamic considerations. Considering the different operating ranges and performance characteristics of the different heat pump technologies it is expected that several industrial heat pump technologies will be needed in the market. Each technology will be able to provide the best solution for a particular combination of waste heat temperature, process heat temperature, the characteristics of the process flows involved (hydro carbons, steam, water), capacity, prices for fuel and electricity, part load operation, and numerous other criteria.

This paper described various developments taking place at the moment to widen the application window of industrial heat pumps resulting in a large energy saving potential at the industrial end-users as well as create new technology for equipment manufacturers.

New closed cycle compression systems for higher temperatures are entering the market on short term. Other developments described will go the same path and it is interesting to notice that new refrigerants will even out the pathway for new technologies and applications in a field that could not have been expected a decade ago.

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